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Causal knowledge and the development of inductive reasoning



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ABSTRACT

We explored the development of sensitivity to causal relations in children's inductive reasoning. Children (5-, 8-, and 12-year-olds) and adults were given trials in which they decided whether a property known to be possessed by members of one category was also possessed by members of (a) a taxonomically related category or (b) a causally related category. The direction of the causal link was either predictive (prey → predator) or diagnostic (predator → prey), and the property that participants reasoned about established either a taxonomic or causal context. There was a causal asymmetry effect across all age groups, with more causal choices when the causal link was predictive than when it was diagnostic. Furthermore, context-sensitive causal reasoning showed a curvilinear development, with causal choices being most frequent for 8-year-olds regardless of context. Causal inductions decreased thereafter because 12-year-olds and adults made more taxonomic choices when reasoning in the taxonomic context. These findings suggest that simple causal relations may often be the default knowledge structure in young children's inductive reasoning, that sensitivity to causal direction is present early on, and that children over-generalize their causal knowledge when reasoning.

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Introduction

Children make category-based inductions when they infer properties and features in novel categories based on what they know to be true about familiar related categories (for reviews, see chapters in

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Feeney & Heit, 2007, and Hayes, Heit, & Swendsen, 2010). Many different types of relations between categories can support such inferences. For example, the fact that *tigers* have a property or that *antelopes* have a property may be equally good evidence that *lions* have the property. The first inference might be strong because lions and tigers are taxonomically related, whereas the second may be strong because lions eat antelopes and this food chain relation provides a plausible causal mechanism for property transmission. This example is consistent with claims based on structured Bayesian approaches to inductive reasoning (see Kemp & Tenenbaum, 2009) that our knowledge about the relations that hold between categories of objects can be structured in a variety of ways. One of our aims in this study was to examine whether causal or taxonomic relations are more privileged in young children's category-based inductive reasoning. It was unclear which knowledge structure might serve as the default because some researchers suggest that taxonomic reasoning is a default strategy (e.g., Kemp & Tenenbaum, 2009; Shafto & Coley, 2003), whereas others emphasize the primacy of causal knowledge (e.g., Rehder, 2006; Rehder, 2009).

Because they are inductive, category-based inferences are probabilistic, but they effectively reduce uncertainty about the world. Understanding the constraints placed on inductive inferences by the underlying structure of different knowledge sources is crucial if we want to understand the processes that allow inductive inferences to be flexible yet effective. Several recent studies (Kemp & Tenenbaum, 2009; Shafto, Kemp, Bonawitz, Coley, & Tenenbaum, 2008) show that adults' inferences are especially sensitive to knowledge about how causal relations are structured. However, little is known about whether children and adults use causal knowledge in similar ways to support their inductive inferences. Our second aim of this study was to examine whether, like adults (see Rehder, 2009; Shafto, Coley, & Baldwin, 2007; Shafto, Coley, & Vitkin, 2007; Shafto et al., 2008), children are sensitive to the direction of the causal relation that holds between categories. Thus, in addition to examining when children's inductive inference becomes sensitive to causal relations, we examined how sophisticated children are in their use of such knowledge for reasoning.

Causal knowledge in inductive reasoning

The effects of causal knowledge on reasoning are not very well captured by older models of category-based induction that emphasize featural similarity (Sloman, 1993) and/or class membership (Osherson, Smith, Wilkie, Lopez, & Shafir, 1990). Such similarity-based models are powerful at accounting for patterns of inductive reasoning about taxonomic properties (i.e., properties such as genes whose distribution in the population may depend on taxonomic relations) and about blank properties (i.e., properties that participants possess no knowledge about). However, they fail to capture induction across a broader variety of properties and in expert populations (see Medin, Coley, Storms, & Hayes, 2003; Rehder & Hastie, 2001; Shafto & Coley, 2003), especially when there is a causal explanation for the occurrence of shared properties (Rehder, 2006).

Causal knowledge plays a vital role in cognition from infancy onward (Sobel & Kirkham, 2007). The ability to understand causal structures provides children with tools that help them to successfully predict future events and understand the outcome of active intervention, allowing them to gain increasing control over their environment (Gopnik et al., 2004). By 4 years of age, children are capable of understanding simple causal mechanisms across the domains of biology (Wellman, Hickling, & Schult, 1997) and psychology (Flavell, Green, & Flavell, 1995) as well as causal explanations in social and physical domains (Hickling & Wellman, 2001). Similarly, children use causal knowledge to classify objects (Ahn, Gelman, Amsterlaw, Hohenstein, & Kalish, 2000) and natural kinds (Meunier & Cordier, 2009).

The fact that children make use of causal information across diverse domains and tasks underscores its potential importance in children's category-based reasoning. Indeed, evidence suggests that children can use causal knowledge when making inductive inferences. For example, Hayes and Thompson (2007) taught children (5- and 8-year-olds) and adults about features of two artificial base creatures, followed by a target that was more similar to one base but shared a causal antecedent with the other base. Results indicated that when the causal link was explicit, all age groups preferred to make causal rather than similarity-based inductions. That is, they preferred to project a property to the target from the causally related base creature than from the more similar base creature. When

the causal relation was implicit, 5-year-olds did not yet show a preference for choosing the causally related items, unlike the older children and adults who made predominantly causal choices. Similarly, [Opfer and Bulloch \(2007\)](#) demonstrated that 5-year-olds were capable of ignoring perceptual similarity in favor of relational similarity when the latter had a causal antecedent but not when it was non-causal. Both of these studies suggest that children's category-based inductive reasoning may be affected by knowledge about causal relations, although they do not allow us to conclude that causal knowledge structures are the default. Moreover, such studies do not address the extent to which children's inductive reasoning is sensitive to the underlying structure of causal knowledge (e.g. [Pearl, 2000](#); [Sloman, 2005](#)). Consequently, we cannot know whether children's use of causal knowledge in induction is mediated by the same underlying processes as in adults.

Structure of causal knowledge: Causal asymmetry effects

An important feature of causal knowledge is that it is directional, with causes always preceding or at least co-occurring with their effects ([Waldmann, 2000](#)). There is evidence that adults take such structural features into account because their causal reasoning tends to display distinctive asymmetry effects ([Fenker, Waldmann, & Holyoak, 2005](#); [Fernbach, Darlow, & Sloman, 2011](#); [Sloman, 2005](#)). Reasoning in line with how we experience cause–effect relations (predictive causal reasoning) appears to be less effortful than reasoning backward (diagnostic causal reasoning), suggesting that computational complexity is a key determinant of the causal asymmetry effect ([Kahneman & Tversky, 1973](#)). For example, when people are asked to verify whether two words are causally related, they respond faster when the words are presented in a predictive order compared with a diagnostic order ([Fenker et al., 2005](#)).

Causal direction also affects inductive inferences. Thus, people find category-based inductive arguments more convincing when reasoning in a predictive direction from cause to effect than when reasoning diagnostically from effect to cause ([Medin et al., 2003](#); [Shafto et al., 2008](#)). To illustrate, people are more confident in the conclusion that *bees* have an unknown property given that it is present in the premise category *flowers* than when the roles of the two categories are reversed. People's judgments appear to accord well with the causal asymmetry effects that are predicted by formal models of causal-based property generalization ([Rehder, 2009](#); [Shafto et al., 2008](#)), although there are arguments that, relative to a normative standard, people have too much confidence in arguments with a predictive structure ([Fernbach et al., 2011](#)). Despite the convincing evidence that the causal asymmetry effect is a robust phenomenon in adults' category-based reasoning, and evidence that children's predictive reasoning about novel mechanical systems is better than their diagnostic reasoning (see [Bindra, Clarke, & Shultz, 1980](#); [Hong, Chijun, Xuemei, Shan, & Chongde, 2005](#)), it is unknown whether children display similar asymmetry effects when they use causal knowledge to support their inductive inferences. Our study was designed to answer this question.

Context-sensitive reasoning

Although it is clear that causal knowledge is important in induction, adults are adept at tailoring their inferences to the particular reasoning context. Consider the example with which we opened this article. If we ask a participant to decide whether lions have a certain gene on the basis that tigers have that gene, then the taxonomic relation that holds between lions and tigers is relevant. On the other hand, if we ask whether lions have a disease on the basis that antelopes have that disease, then the causal mechanism for disease transmission from antelope to lions via predation is relevant. There is much evidence that adults, and sometimes children, can show inductive selectivity by selecting the appropriate knowledge with which to evaluate category-based inductive arguments. For example, [Heit and Rubinstein \(1994\)](#) showed that people make stronger inferences about shared properties when the nature of the property is in accord with the nature of the relationship between two categories. According to [Shafto, Coley, and Baldwin \(2007\)](#); [Shafto, Coley, and Vitkin \(2007\)](#), changes in context affect the acute availability of different knowledge structures. Thus, when reasoning about properties such as diseases, people are more inclined to use knowledge about causal or ecological

relations, whereas taxonomic knowledge tends to be invoked when reasoning about anatomical properties.

There is some evidence that children are also sensitive to the nature of the property that they are reasoning about (for a full review, see [Hayes, 2006](#)). [Nguyen and Murphy \(2003\)](#), for example, showed that by 7 years of age, children reason taxonomically about biochemical features but use thematic relations to guide inferences about situational properties. However, in their study younger children's use of different relations was heavily influenced by task format, making it difficult to evaluate the degree to which these children were using different knowledge structures in a systematic manner. [Coley \(2012\)](#) demonstrated that there are environmental influences on the age by which children show inductive selectivity; by 10 years of age, children raised in urban environments selectively project disease properties between categories that are ecologically related and so suggest a causal mechanism for disease transmission, whereas rural children show the same pattern as early as 6 years of age. In an open-ended category generation task, [Vitkin, Coley, and Hu \(2005\)](#) also showed that children's inferences are constrained by the nature of the property that they are asked to reason about. Thus, when told that the two categories share "stuff inside," children generated categories based on similarity, whereas they gave interaction-based responses when reasoning about shared diseases.

In this study we manipulated the nature of the property that participants were asked to reason about. Although we expected adults to show property effects, our aim in this study was not to assess the age by which children demonstrate inductive selectivity because any answer to this question will depend on the paradigm employed. Indeed, inductive selectivity effects have been demonstrated in young children ([Heyman & Gelman, 2000a](#); [Heyman & Gelman, 2000b](#)) and even infants (see [Mandler & McDonough, 1998](#); [Rakison & Hahn, 2004](#)). Instead, we wanted to examine, in the domain of folk biology, how children reason before selectivity emerges and whether a particular knowledge structure is more important.

On the basis of the literature, it is very difficult to answer questions about default knowledge structures. There appears to be reason for assuming that taxonomic knowledge structures are the default; for example, using a speeded response paradigm, [Shafto and colleagues \(2007\)](#) showed that access to knowledge about causal mechanisms for disease transmission due to ecological relations between categories is restricted when adults are asked to respond quickly, whereas taxonomic knowledge seems unaffected by response time manipulations. This finding, that taxonomic knowledge is primary, is consistent with suggestions that taxonomic knowledge structures are the default ([Kemp & Tenenbaum, 2009](#)). However, there is also reason to believe that taxonomic knowledge structures are not the default; [Rehder \(2006\)](#), [Rehder \(2009\)](#) emphasized the primacy of causal knowledge over taxonomic knowledge, and there is evidence that young children prefer to use thematic knowledge rather than taxonomic knowledge when reasoning about categories (see [Greenfield & Scott, 1986](#); [Nguyen & Murphy, 2003](#); [Smiley & Brown, 1979](#)).

Because the developmental literature is divided on the question of how young children reason inductively, there are also important theoretical questions about the development of inductive reasoning to which questions of default knowledge are relevant. [Sloutsky \(2010\)](#) theorized that inductive selectivity depends on a maturationally late learning system. Sloutsky suggested that, prior to the emergence of inductive selectivity, children rely on knowledge acquired through a simple learning system that exploits co-occurrences and similarity. He cited evidence that before 7 years of age children rely largely on such similarity between base and target category to guide their inferences ([Fisher & Sloutsky, 2005](#); [Rakison & Lupyan, 2008](#); [Sloutsky & Fisher, 2004](#)). This would suggest that prior to the emergence of inductive selectivity, children ought to rely heavily on superficial similarity or category membership rather than on causal knowledge. However, there is evidence that even children as young as 5 years can ignore featural similarity when explicit causal knowledge is available ([Hayes & Thompson, 2007](#); [Opfer & Bulloch, 2007](#)).

Here we examined whether children as young as 5 years prefer to reason on the basis of taxonomic or causal relations. This group was younger than the youngest participants that [Coley \(2012\)](#) found to display inductive selectivity. The contradictory findings in the literature made it hard to predict whether these children will prefer arguments with taxonomic or causal relations and whether they will be sensitive to causal structure. If young children's inductive inferences are dominated by taxonomic relations, then we would expect to see few effects of causal knowledge. If, on the other hand,

causal knowledge dominates early in reasoning development, then the question arises as to whether young children will exhibit causal asymmetry effects.

Method

Participants

In total, 44 Year 1 primary school children ($M_{\text{age}} = 5.4$ years), 40 Year 4 primary school children ($M_{\text{age}} = 8.4$ years), 54 Year 8 secondary school children ($M_{\text{age}} = 12.6$ years), and a control group of 26 adults from Durham University ($M_{\text{age}} = 24.6$ years) in the United Kingdom took part in the experiment. Year 1 and Year 4 students were recruited from a suburban state primary school in the North East of England. Year 8 students were recruited from a suburban state secondary school in the same geographical area. There were approximately equal numbers of male and female participants in the various age groups.

Design

The experiment had a 4 (Age Group: 5-year-olds, 8-year-olds, 12-year-olds, or adults) \times 2 (Property: disease or cells) \times 2 (Direction: predictive or diagnostic) \times 2 (List: A or B) mixed design, with repeated measures on the direction variable only.

Materials

Participants reasoned about 12 trials, each consisting of a triad of categories: a base and two targets. On each trial, participants were presented with a base category, were told that it possessed a feature, and were asked which of the target categories they thought was most likely to share that feature. One of the targets was causally related to the base in the form of a food chain relation. This causally related target category always belonged to a different superordinate category from the base. The other target category was taxonomically related to the base category and was from the same superordinate category as the base. In the *predictive* condition, the causal direction was ecologically consistent. For example, the base category might be a banana and the causally related target might be a monkey. In the *diagnostic* version of this example, the directionality of the causal link was reversed so that the monkey served as the base and the banana served as the target. To ensure that children understood the causal mechanisms by which two categories might be connected, the nature of the causal relationship was limited to transparent food chains. An example with pictures, all of which were selected from [Rossion and Pourtois \(2004\)](#) database, is shown in [Fig. 1](#).

The direction of the causal link was counterbalanced across items. For List A, the causal direction was predictive for Items 1 to 6 and was diagnostic for Items 7 to 12; for List B, the opposite was the case. Thus, although direction was a within-participants factor, participants never saw any of the causal pairs twice. The task was self-paced and run on a laptop using purpose-built software.

So that the causally related pairs could be presented in either a predictive direction (e.g., carrot \rightarrow horse) or a diagnostic direction (e.g., horse \rightarrow carrot), different categories served as the base (e.g., carrot or horse). Because the taxonomically related target category belonged to the same superordinate category as the base category, this meant that the taxonomically related target category was different on diagnostic and predictive trials. Thus, it was crucial to equate the similarity between the base instance and the taxonomic alternative targets across predictive conditions (e.g., carrot \rightarrow onion) and diagnostic conditions (e.g., horse \rightarrow sheep).

A group of 18 Durham University students rated the similarity on a scale from 1 (*not at all similar*) to 9 (*highly similar*) between pairs of categories presented verbally in a pretest. Only triads in which the similarity ratings were approximately equal across both conditions were selected (all paired-sample *t* tests had p s $> .05$), resulting in 12 triads. Mean similarity ratings by triad are presented in [Appendix Table A1](#)). Although we did not collect similarity ratings from children, there is evidence that children and adults perceive similarity relations in similar ways. For example, using materials

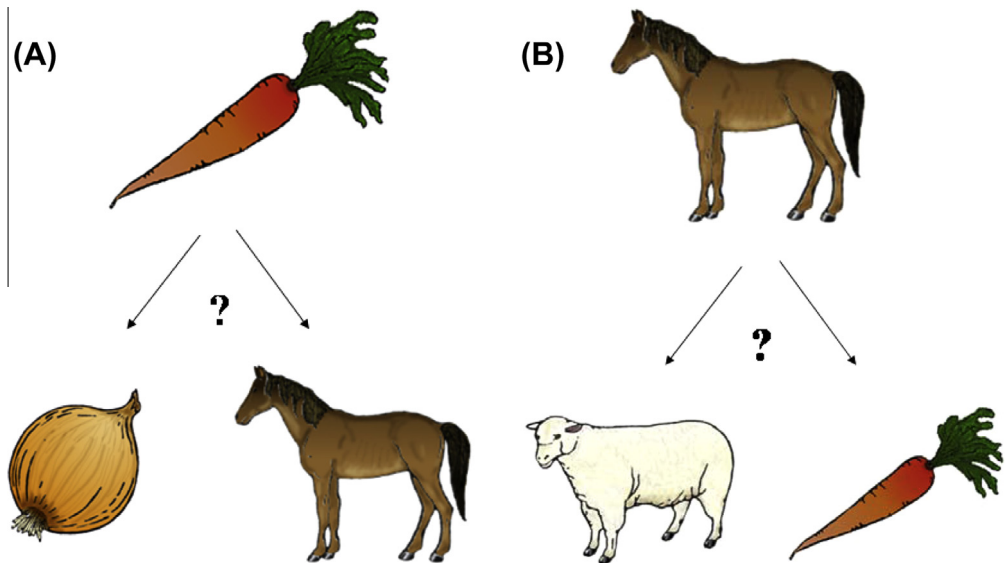


Fig. 1. (A) Triad with predictive causal link. (B) Triad with diagnostic causal link.

pretested for similarity with adults by Osherson and colleagues (1990), López, Gelman, Gutheil, and Smith (1992) showed effects of similarity on reasoning in 5-year-olds that were identical to the similarity effects originally found in adults by Osherson and colleagues.

The strength of the causal relation between the base and target categories was examined in a separate pretest on 19 Durham University students who rated the extent to which properties might be transmitted between the base and both target categories in each triad on a scale from 1 (*not at all*) to 9 (*a great deal*). In all cases, ratings were stronger for causally related categories than for taxonomically related categories. These differences were statistically significant ($p < .05$) in 9 of 12 cases and were marginally significant in the remaining 3 cases (see Appendix Table A2 for ratings).

Procedure

Parents received written information about the study with an opt-out form in case they did not want their children to take part. Children gave their assent at the beginning of the session.

Participants were randomly allocated to either the cell or disease condition. The task was explained verbally, and written instructions were presented on-screen. Participants completed 2 practice trials before commencing the main task. They saw a base picture at the top of the screen and were told that the animal, plant, or object had an unfamiliar disease or special cells (e.g., “This horse has a disease called talio/has talio cells inside”). A different artificial cell or disease name was used for each trial. The base picture was followed by two arrows pointing to two target pictures. Participants decided which of the two pictures was more likely to share the disease or special cells with the base category. The location of the causally and taxonomically related targets on the screen was randomized. Participants pressed 1 if they thought that the left-hand picture was more likely to share the property and pressed 9 if they chose the right-hand picture.

Results

For each individual, the proportion of causally related targets that were chosen was calculated for the six predictive and six diagnostic triad items. These were analyzed using a 2 (Direction) \times 4 (Age Group) \times 2 (Property) \times 2 (List) mixed-design analysis of variance (ANOVA) with direction as the only

within-participants variable. For the item analysis, proportions of causal choices were averaged across items rather than participants.

All effects involving the counterbalancing list variable were nonsignificant (all p s > .10), so there is no further reference to this variable.

As predicted, there was a main effect of direction, $F_s(1, 146) = 20.8, p < .0005$, effect size $f = .38$, $F_i(1, 11) = 21.4, p = .001$, and a significant main effect of age group, $F_s(1, 146) = 6.5, p < .0005$, effect size $f = .37$, $F_i(1.9, 21.3) = 22.56$ (Greenhouse–Geisser adjustment for non-sphericity), $p < .0005$. Participants made significantly more causal inferences when the link between the causally related categories was predictive ($M = .60, SE = .026$) than when it was diagnostic ($M = .47, SE = .028$). Despite the significant main effects, the interaction between age group and direction did not approach significance, $F_s(2, 146) = 0.21, p = .89$, effect size $f = .006$, $F_i(3, 33) = 0.55, p = .66$. Rather, as may be seen in Table 1, children were as strongly influenced by the structure of causal knowledge as were adults.

Post hoc comparisons using Bonferroni adjustments on the means involved in the significant effect of age group showed that 8-year-olds made more causal choices than both 12-year-olds ($p = .05$) and adults ($p < .0005$). There was no significant difference in the proportion of causal choices made by 12-year-olds and adults ($p = .17$), and 5-year-olds made significantly more causal choices than adults ($p = .014$). Both 5-year-olds, $t(43) = 2.69, p = .001$, and 8-year-olds, $t(39) = 3.91, p < .0005$, made more causal choices than predicted by chance alone.

The trend line in Fig. 2 suggests that causal induction shows a curvilinear development in the shape of an inverted U, which was confirmed with a polynomial contrast. This involves starting with the linear contrast and then sequentially carrying out higher power contrasts until the highest-power

Table 1
Mean proportions of causal inferences (and standard deviations) across age groups.

Age group	Causal direction		
	Predictive	Diagnostic	Total
5-year-olds	.67 (.30)	.51 (.32)	.59 (.21)
8-year-olds	.74 (.29)	.60 (.37)	.67 (.28)
12-year-olds	.57 (.39)	.46 (.37)	.51 (.35)
Adults	.42 (.40)	.32 (.35)	.37 (.35)
Total	.62 (.36)	.48 (.36)	.55 (.32)

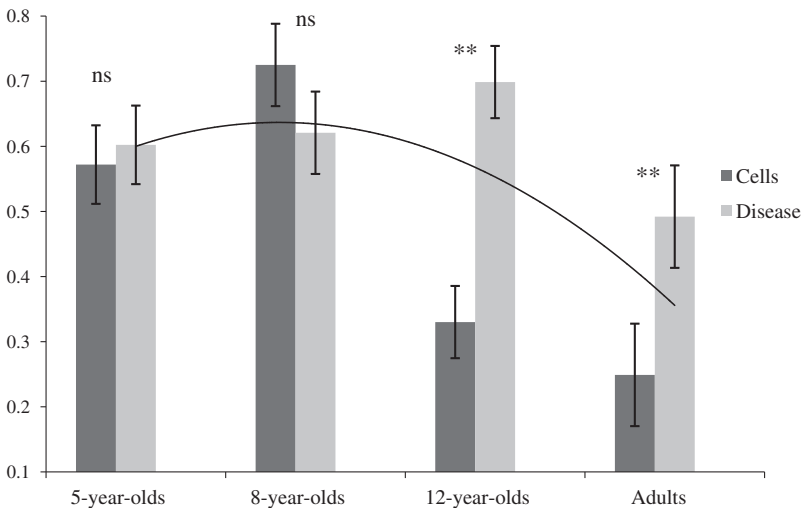


Fig. 2. Mean proportions of causal choices (and standard error bars) at different ages across two types of property. ** $p < .01$.

contrast is nonsignificant. There was a significant linear trend ($p < .0005$) as well as a significant quadratic term ($p = .014$). The cubic contrast was nonsignificant ($p = .18$). The quadratic effect across age group was also highly significant across items, $F_1(1, 11) = 15.7$, $p < .0005$. This pattern confirms that the use of causal knowledge in inductive reasoning follows a curvilinear developmental trajectory, peaking at 8 years and decreasing thereafter.

The results of the ANOVA contained a significant main effect of property, $F_5(1, 146) = 8.6$, $p = .004$, effect size $f = .24$, $F_1(1, 11) = 60.9$, $p < .0005$. Causal choices were significantly more frequent when participants reasoned about diseases ($M = .60$, $SE = .033$) than when they reasoned about cells ($M = .47$, $SE = .033$). However, this was qualified by a significant interaction between property and age group, $F_5(2, 106) = 6.2$, $p = .001$, effect size $f = .36$, $F_1(3, 33) = 62.7$, $p < .0005$. As Fig. 2 shows, both 4- and 8-year-olds made a similar number of causal inductions in both the cell and disease conditions ($ps > .25$, effect size $d < 0.2$), suggesting that they are not exhibiting strong inductive selectivity effects. In contrast, both adults ($p = .031$, effect size $d = 0.8$) and 12-year-olds ($p = .0005$, effect size $d = 1.2$) showed strong inductive selectivity effects, making significantly more causal inductions in the disease condition than in the cell condition.

Furthermore, the proportion of causal choices was similar across all age groups when reasoning about diseases (all pairwise comparison $ps > .20$). In contrast, when reasoning about cells, 4- and 8-year-olds made significantly more causal choices than both 12-year-olds and adults ($ps < .022$). The latter two age groups were not significantly different from each other ($p = .64$). Thus, it appears that the increased selectivity is driven by a developmental decrease in causal choices when reasoning about cells rather than a change in the application of causal knowledge when reasoning about diseases.

There was no significant interaction between direction and property, $F_5(1, 146) = 2.26$, $p = .13$, effect size $f = .12$, $F_1(1, 11) = 2.94$, $p = .11$, and no three-way interaction among age group, property, and direction, $F_5(3, 146) = 0.93$, $p = .43$, effect size $f = .13$, $F_1(3, 33) = 0.89$, $p = .46$.

Our results appear to show that children do not display inductive selectivity until 12 years of age and that before that age they prefer to use causal knowledge when evaluating inferences. In addition, children as young as 5 years are as sensitive to causal structure as are adults. To rule out alternative accounts of children's preference for causally related targets, we carried out a number of posttests. One possibility is that the causally related category pairs were more strongly associated or co-occur more frequently than the taxonomically related category pairs. This would then give the impression that children were reasoning causally, whereas in fact the results would be explicable in terms of co-occurrence and associations (Sloutsky & Fisher, 2008). Remember that in our pretests we ensured that the different taxonomically related targets in the predictive and diagnostic conditions were equally associated with the base category, but we did not check whether the degree of association between the base category and each of the targets was approximately equal. Associations between words tend to be reflected in how we use language; words that co-occur more frequently are more strongly associated in semantic memory (Spence & Owens, 1990). One way to guard against the possibility that our materials are confounded by associative strength is to look at the frequency of co-occurrence between two words in a text or sentence (Church & Hanks, 1990; Ide & Veronis, 1998; Rapp & Wettler, 1991). The World Wide Web provides an almost infinite source of linguistic data. Using a Google proximity search specifying that the categories must co-occur in any order within a window of six consecutive words (Canas, 1990), we calculated the conditional co-occurrence of the taxonomic and causal category pairs using the following formula suggested by Heylighen (2001):

$$Aw_1 \& w_2 = P(w_1 | w_2) = \frac{P(w_1 \& w_2)}{P(w_1)} = \frac{N(w_1 \& w_2)}{N(w_1)}$$

In this equation, $P(w_1 \& w_2)$ represents the probability that a text contains both words w_1 and w_2 , and $P(w_1)$ represents the probability that it contains w_1 on its own. To calculate the conditional probability, one can simply count the number of times w_1 and w_2 co-occur and divide this by the number of times w_1 occurs by chance in the same text sample. This is repeated for w_2 . We took the mean of the two conditional probabilities for each pair and calculated z scores. Using an independent-samples t test, we compared the mean co-occurrence index for the causally related category pairs (mean z

score = -0.3 , $SD = 0.4$) with the mean co-occurrence index for the taxonomically related category pairs (mean z score = 0.15 , $SD = 1.2$). This showed that there was no significant difference between the two co-occurrence indexes, $t = 1.68$, $df = 31.3$ (adjusted for unequal variances), $p = .10$, effect size $d = 0.5$. However, as indicated by the medium effect size, if anything the taxonomic category pairs co-occurred slightly more frequently, strengthening our claim that children and adults were drawing on structured causal knowledge rather than simple associative knowledge.

Another possible alternative explanation of our results is that the youngest participants preferred causally related targets because they did not possess the knowledge about taxonomic relations required to recognize the strength of arguments based on such relations. To rule out this possibility, we checked taxonomic and causal knowledge levels in a separate sample of the same age as our youngest age group. A group of 20 5-year-olds were shown the color pictures of the category pairs used in the main experiment and were asked about biological group membership (“Do this [name of first category] and this [name of second category] belong to the same group?”) and causal relatedness (“Does this [name of first category] eat this [name of second category]?”). Paired-samples t tests across the 20 children and by items showed that there was no difference between the causal relatedness endorsement proportion ($M = .78$, $SD = .13$) and the biological group membership endorsement proportion ($M = .79$, $SD = .17$), $t_s(19) = -0.68$, $p = .51$, effect size $d = 0.15$, $t_i(11) = -0.037$, $p = .97$. Thus, it is unlikely that the 5- and 8-year-olds in the main experiment preferred causal targets because, relative to their causal knowledge, they lacked taxonomic knowledge.

Discussion

We had two aims in carrying out this study. First, we wanted to examine whether causal or taxonomic knowledge is the default prior to the age at which children develop inductive selectivity. Second, we wanted to see whether children are sensitive to aspects of causal structure when evaluating category-based inductive arguments. In showing that 5- and 8-year-old participants preferred arguments that were strong because of a causal mechanism for transmission via a predation relation even when the property reasoned about was a cell, our findings suggest that causal knowledge structures are the default in children’s reasoning prior to the emergence of inductive selectivity. In addition, 5-year-olds are just as sensitive to causal direction as are adults. In fact, all age groups in our experiment endorsed significantly more predictive arguments than diagnostic arguments. Interestingly, causal reasoning seems to show a curvilinear development, peaking at 8 years of age and decreasing thereafter due to the emergence of inductive selectivity. Although we did not anticipate this last finding, as we show below, it has parallels in the literature on children’s understanding of folk biology.

The pattern of results we observed has very interesting implications for theories about how inductive reasoning develops. Sloutsky (2010) suggested that “adult-like” inductive reasoning depends on a maturationally late learning system. This suggestion can explain why we did not observe inductive selectivity until the age of 12 years, driven by an increase in taxonomic inferences when reasoning about cells. Under Sloutsky’s account, reasoning about cells might require more abstract conceptual knowledge about mechanisms that are not perceptually observable such as genetics and inheritance. However, this account also seems to suggest that prior to the emergence of inductive selectivity children ought to rely heavily on superficial similarity or category membership rather than on causal knowledge. Our data suggest otherwise, with 5- and 8-year-olds making the most causal inductions regardless of context. Alongside recent evidence from Hayes and Lim (2013), who showed that inductive selectivity even in relatively transparent contexts depends on conscious awareness of the relevance of contextual clues, the current findings cast doubt on the claim that early category-based induction is driven exclusively by simple learning mechanisms based on co-occurrence and perceptual similarity. At the very least, it requires a substantial downward revision of the age at which conceptual knowledge such as simple causal structures can support category-based inductive reasoning.

In addition to their tendency to prefer causal relations rather than taxonomic relations as the basis for inference, 5- and 8-year-old participants, like older participants, made more causal inferences when the causal relation between the categories was predictive than when it was diagnostic. The influence of different kinds of knowledge seems to be fundamentally related to the way in which this

knowledge is organized in long-term memory (Fenker et al., 2005). Although causal knowledge itself does not have a homogeneous structure and can vary in complexity from direct cause–effect links to more complex common cause relations (Sloman, 2005), one might expect the abstract organization of knowledge about food chains involving simple causal transmission to be similar in adults and children. For example, children as young as 3 years show an understanding of the importance of causal order in which effects follow or co-occur with their causes (Bullock & Gelman, 1979; Bullock, Gelman, & Baillargeon, 1982). Reasoning about relations that are in line with this ordering of events might be cognitively simpler than needing to reason about possible causes given an outcome (Kahneman & Tversky, 1973). Shafto and colleagues (2008) suggested that causal asymmetry effects are driven by a multilevel understanding of causal knowledge—concrete knowledge about the existence of causal relations and more conceptual knowledge about how and when causal relations are most likely to warrant an inference from one agent to another.

The simple causal structure used in the current task might explain why some of our findings are different from previous results. For example, whereas the current study showed no age-related changes in the frequency of causal reasoning about diseases, work on ecological reasoning by Coley, Vitkin, Seaton, and Yopchick (2005) demonstrates a clear developmental trend in the use of non-taxonomic knowledge. They argued that this is driven by an experiential increase in ecological knowledge. It is conceivable that the structure of the causal relations underlying the ecologically related categories in Coley and colleagues' study (e.g., between tiger and parrot) was more complex, involving indirect causal pathways and common causes rather than simple and direct cause–effect relations. Thus, increased complexity may render non-taxonomic knowledge less available to reasoning processes in younger children.

There may be a number of reasons why the younger children in our experiment relied on causal knowledge rather than taxonomic knowledge when reasoning. The properties used required knowledge about two quite distinctive biological domains: (a) food chain relations and disease contagion and (b) taxonomic relations and genetics. One likely possibility is that knowledge of the genetic basis of shared properties, inheritance, and biological processes is less elaborate in 5- and 8-year-olds compared with 12-year-olds and adults (Au & Romo, 1999; Hatano & Inagaki, 1994; Hatano & Inagaki, 1997). Indeed, educational research suggests that children have conceptual gaps and erroneous concepts in their explanations for genetics (Lewis & Kattmann, 2004; Smith & Williams, 2007) that become more elaborate and accurate only with explicit instruction (Venville & Donovan, 2007). On the other hand, the mechanism by which members of a common food chain may transmit diseases is obvious and observable and constitutes a central part of the science curriculum for 8-year-olds. In line with other work showing that children like to have an explanation for phenomena (Callanan & Oakes, 1992), the children in our study may have preferred to base their reasoning on relations for which they have a mechanistic explanation and a more coherent theory (Gutheil, Vera, & Keil, 1998). Children as young as 3 years have a basic appreciation that invisible agents can cause illness (Kalish, 1996) and understand simple mechanisms by which contamination may come about (Siegal & Share, 1990; Springer & Belk, 1994), suggesting that children do have some naive but systematic theory about biological disease transmission.

One striking aspect of our results was that younger participants over-generalized their knowledge of disease transmission mechanisms. A relevant example of knowledge over-generalization comes from Keil and colleagues (1999), who showed that increases in knowledge about the mechanisms of disease transmission simultaneously led to more accurate inductions for physical illness contagion but less accurate reasoning about the causes of mental illness. Interestingly, the 8-year-old participants in Keil and colleagues' study made the most inaccurate transmission choices. This over-generalization parallels our current finding in which simple causal transmission is also seen as a basis for sharing physiological properties such as cells. Thus, inaccurate beliefs or inappropriate causal explanations seem to be supplanted only when children have more appropriate coherent explanatory systems at their disposal.

Because they show that causal knowledge dominates taxonomic knowledge in young reasoners, our results are contrary to the claim made by proponents of the structured Bayesian approach that taxonomic knowledge structures are the default (see Kemp & Tenenbaum, 2009; Tenenbaum, Kemp, & Shafto, 2007). Nonetheless, theory-driven Bayesian approaches have the potential to explain

developmental changes in patterns of inductive reasoning. The domain-specific theories captured in Bayesian knowledge structures are minimalist and open to revision, both on encountering direct evidence and through verbal instruction. These characteristics of the Bayesian account, in conjunction with the observation that children are likely to have less well-developed domain-specific theories, may allow the Bayesian approach to account for the divergence between 8-year-olds' and adults' patterns of inductive selectivity. However, it aims to explain inference at a computational level rather than in terms of process; the Bayesian approach does not address the issues of availability and processing effort (Shafto, Coley, & Baldwin, 2007; Shafto, Coley, & Vitkin, 2007) that are likely to be important when explaining developmental changes in reasoning ability.

Finally, our research made use of non-blank properties such as cells and diseases, with inductive selectivity driven by the decrease in the use of causal relations when reasoning about cells. A future interesting question will be to explore the developmental use of causal knowledge for inductive problems that use blank properties. It seems likely that changes in the application of causal knowledge would be driven by cultural factors and expertise with causal choices likely to decrease in Western and/or urban samples, whereas the use of causal knowledge is likely to persist in non-Western and more rural samples (e.g., Coley, 2012; Lopez, Atran, Coley, Medin, & Smith, 1997). To summarize, young children strongly prefer inductive arguments where there is a plausible causal mechanism for property transmission, even where older children and adults appear to judge that mechanism irrelevant to the property to be generalized. Recruitment of this salient source of knowledge may be supplanted only by more contextually appropriate knowledge when formal education offers children an alternative feasible mechanism by which two categories come to share properties. In addition, even 5-year-olds are influenced by the directional nature of causal relations. All of this suggests that causal relations are at least as important to young children's reasoning as they are to adults' reasoning and that, in some respects, the manner in which causal reasoning influences reasoning is similar across development.

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Appendix

Table A1

Pretest similarity ratings for the 12 triads.

Causally related category pair	Similarity rating for taxonomically related categories in predictive condition	Similarity rating for taxonomically related categories in diagnostic condition
Peanut–Monkey	Peanut–Acorn (4.94) [*]	Monkey–Zebra (4.56) [*]
Carrot–Horse	Carrot–Onion (5.61) [*]	Horse–Deer (5.78) [*]
Sandwich–Human	Sandwich–Cake (5.28) [*]	Human–Gorilla (5.72) [*]
Lettuce–Snail	Lettuce–Potato (4.44) [*]	Snail–Octopus (3.67) [*]
Apple–Caterpillar	Apple–Lemon (5.17) [*]	Caterpillar–Ant (5.06) [*]
Worm–Sparrow	Worm–Dragonfly (4.06) [*]	Sparrow–Chicken (3.89) [*]
Salmon–Bear	Salmon–Ray (5.61) [*]	Bear–Lion (5.06) [*]
Flower–Butterfly	Flower–Tree (5.72) [*]	Butterfly–Grasshopper (4.89) [*]
Cheese–Mouse	Cheese–Cake (4.56) [*]	Mouse–Rabbit (4.89) [*]
Acorn–Squirrel	Acorn–Peanut (4.94) [*]	Squirrel–Rat (4.56) [*]
Banana–Monkey	Banana–Peach (5.44) [*]	Monkey–Elephant (4.56) [*]
Carrot–Rabbit	Carrot–Green pepper (4.44) [*]	Rabbit–Sheep (4.33) [*]

^{*} None of the similarity ratings was significantly different.

Table A2

Pretest causal strength ratings for the 12 triads.

Causal strength rating for causally related category pair	Causal strength rating for taxonomically related category in predictive condition	Causal strength rating for taxonomically related category in diagnostic condition
Peanut–Monkey (7.05)	Peanut–Acorn (4.42)	Monkey–Zebra (3.11)
Carrot–Horse (7.00)	Carrot–Onion (4.05)	Horse–Deer (4.11)
Sandwich–Human (7.89)	Sandwich–Cake (4.37)	Human–Gorilla (4.47)
Lettuce–Snail (7.37)	Lettuce–Potato (3.05)	Snail–Octopus (2.68)
Apple–Caterpillar (5.32)	Apple–Lemon (3.79)	Caterpillar–Ant (3.95)
Worm–Sparrow (7.89)	Worm–Dragonfly (3.53)	Sparrow–Chicken (3.79)
Salmon–Bear (6.37)	Salmon–Ray (4.00)	Bear–Lion (3.79)
Flower–Butterfly (6.58)	Flower–Tree (4.40)	Butterfly–Grasshopper (5.00)
Cheese–Mouse (7.74)	Cheese–Cake (5.37)	Mouse–Rabbit (4.00)
Acorn–Squirrel (7.42)	Acorn–Peanut (4.42)	Squirrel–Rat (4.16)
Banana–Monkey (7.53)	Banana–Peach (3.84)	Monkey–Elephant (4.00)
Carrot–Rabbit (7.95)	Carrot–Green pepper (3.11)	Rabbit–Sheep (4.21)

References

- Ahn, W. K., Gelman, S. A., Amsterlaw, J. A., Hohenstein, J., & Kalish, C. W. (2000). Causal status effect in children's categorization. *Cognition*, 76, 35–43.
- Bindra, D., Clarke, K. A., & Shultz, T. R. (1980). Understanding predictive relations of necessity and sufficiency in formally equivalent "causal" and "logical" problems. *Journal of Experimental Psychology: General*, 109, 422–443.
- Bullock, M., & Gelman, R. (1979). Preschool children's assumptions about cause and effect—temporal ordering. *Child Development*, 50, 89–96.
- Bullock, M., Gelman, R., & Baillargeon, R. (1982). The development of causal reasoning. In W. J. Friedman (Ed.), *The developmental psychology of time* (pp. 209–254). New York: Academic Press.
- Callanan, M. A., & Oakes, L. M. (1992). Preschoolers' questions and parents' explanations: Causal thinking in everyday activity. *Cognitive Development*, 7, 213–233.
- Canas, J. J. (1990). Associative strength effects in the lexical decision task. *Quarterly Journal of Experimental Psychology Section a—Human Experimental Psychology*, 42(1), 121–145.
- Church, K. W., & Hanks, P. (1990). *Word association norms, mutual information, and lexicography*. Morristown, NJ: Association of Computational Linguistics.
- Coley, J. D. (2012). Where the wild things are: Informal experience and ecological reasoning. *Child Development*, 83, 992–1006.
- Coley, J. D., Vitkin, A. Z., Seaton, C. E., & Yopchick, J. E. (2005). Effects of experience on relational inferences in children: The case of folk biology. In B. G. Bara, L. Barsalou, & M. Bucciarelli (Eds.), *Proceedings of the 27th annual conference of the Cognitive Science Society* (pp. 471–475). Mahwah, NJ: Lawrence Erlbaum.
- Feeney, A., & Heit, E. (2007). *Inductive reasoning*. Cambridge, UK: Cambridge University Press.
- Fenker, D. B., Waldmann, M. R., & Holyoak, K. J. (2005). Accessing causal relations in semantic memory. *Memory & Cognition*, 33, 1036–1046.
- Fernbach, P. M., Darlow, A., & Sloman, S. A. (2011). Asymmetries in predictive and diagnostic reasoning. *Journal of Experimental Psychology: General*, 140, 168–185.
- Fisher, A. V., & Sloutsky, V. M. (2005). When induction meets memory: Evidence for gradual transition from similarity-based to category-based induction. *Child Development*, 76(3), 583–597.
- Flavell, J. H., Green, F. L., & Flavell, E. R. (1995). Young children's knowledge about thinking. *Monographs of the Society for Research in Child Development*, 60, 5–95.
- Gopnik, A., Glymour, C., Sobel, D. M., Schulz, L. E., Kushnir, T., & Danks, D. (2004). A theory of causal learning in children: Causal maps and Bayes nets. *Psychological Review*, 111, 3–32.
- Greenfield, D. B., & Scott, M. S. (1986). Young children's preference for complementary pairs: Evidence against a shift to a taxonomic preference. *Developmental Psychology*, 22, 19–21.
- Gutheil, G., Vera, A., & Keil, F. C. (1998). Do houseflies think? Patterns of induction and biological beliefs in development. *Cognition*, 66, 33–49.
- Hatano, G., & Inagaki, K. (1994). Young children's naive theory in biology. *Cognition*, 50, 171–188.
- Hatano, G., & Inagaki, K. (1997). Qualitative changes in intuitive biology. *European Journal of Psychology of Education*, 12, 111–130.
- Hayes, B. K., Heit, E., & Swendsen, H. (2010). Inductive reasoning. *Wiley Interdisciplinary Reviews: Cognitive Science*, 1, 278–292.
- Hayes, B., & Lim, M. (2013). Development, awareness and inductive selectivity. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 39(3), 821–831.
- Hayes, B. K. (2006). Knowledge, development, and category learning. In B. H. Ross (Ed.), *Advances in research and theory. Psychology of learning and motivation* (Vol. 46, pp. 37–77). San Diego: Elsevier.
- Hayes, B. K., & Thompson, S. P. (2007). Causal relations and feature similarity in children's inductive reasoning. *Journal of Experimental Psychology: General*, 136, 470–484.
- Heit, E., & Rubinstein, J. (1994). Similarity and property effects in inductive reasoning. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 20, 411–422.
- Heylighen, F. (2001). Mining associative meanings from the Web: From word disambiguation to the global brain. In R. Temmerman (Ed.), *Proceedings of Trends in Special Language and Language Technology*. Standaard: Brussels, Belgium.

- Heyman, G. D., & Gelman, S. A. (2000a). Preschool children's use of novel predicates to make inductive inferences about people. *Cognitive Development*, 15, 263–280.
- Heyman, G. D., & Gelman, S. A. (2000b). Preschool children's use of trait labels to make inductive inferences. *Journal of Experimental Child Psychology*, 77, 1–19.
- Hickling, A. K., & Wellman, H. M. (2001). The emergence of children's causal explanations and theories: Evidence from everyday conversation. *Developmental Psychology*, 37, 668–683.
- Hong, L., Chijun, Z., Xuemei, G., Shan, G., & Chongde, L. (2005). The influence of complexity and reasoning direction on children's causal reasoning. *Cognitive Development*, 20, 87–101.
- Ide, N., & Veronis, J. (1998). Introduction to the special issue on word sense disambiguation: The state of the art. *Computational Linguistics*, 24, 1–40.
- Kahneman, D., & Tversky, A. (1973). Psychology of prediction. *Psychological Review*, 80, 237–251.
- Kalish, C. W. (1996). Preschoolers' understanding of germs as invisible mechanisms. *Cognitive Development*, 11, 83–106.
- Keil, F. C., Levin, D. T., Richman, B. A., & Guthrie, G. (1999). Mechanism and explanation in the development of biological thought: The case of disease. In D. Medin & S. Atran (Eds.), *Folkbiology* (pp. 233–284). Cambridge, MA: MIT Press.
- Kemp, C., & Tenenbaum, J. B. (2009). Structured statistical models of inductive reasoning. *Psychological Review*, 116, 20–58.
- Lewis, E., & Kattmann, U. (2004). Traits, genes, particles, and information: Re-visiting students' understandings of genetics. *International Journal of Science Education*, 26, 195–206.
- Lopez, A., Atran, S., Coley, J. D., Medin, D. L., & Smith, E. E. (1997). The tree of life: Universal and cultural features of folkbiological taxonomies and inductions. *Cognitive Psychology*, 32, 251–295.
- López, A., Gelman, S. A., Guthrie, G., & Smith, E. E. (1992). The development of category-based induction. *Child Development*, 63, 1070–1090.
- Mandler, J. M., & McDonough, L. (1998). Studies in inductive inference in infancy. *Cognitive Psychology*, 37, 60–96.
- Medin, D. L., Coley, J. D., Storms, G., & Hayes, B. K. (2003). A relevance theory of induction. *Psychonomic Bulletin & Review*, 10, 517–532.
- Meunier, B., & Cordier, F. (2009). The role of feature type and causal status in 4–5-year-old children's biological categorizations. *Cognitive Development*, 24, 34–48.
- Nguyen, S. P., & Murphy, G. L. (2003). An apple is more than just a fruit: Cross-classification in children's concepts. *Child Development*, 74, 1783–1806.
- Opfer, J. E., & Bulloch, M. J. (2007). Causal relations drive young children's induction, naming, and categorization. *Cognition*, 105, 206–217.
- Osherson, D. N., Smith, E. E., Wilkie, O., Lopez, A., & Shafir, E. (1990). Category-based induction. *Psychological Review*, 97, 185–200.
- Pearl, J. (2000). *Causality: Models, reasoning, and inference*. Cambridge, UK: Cambridge University Press.
- Rakison, D. H., & Hahn, E. R. (2004). The mechanisms of early categorization and induction: Smart or dumb infants? *Advances in Child Development and Behavior*, 32, 281–322.
- Rakison, D. H., & Lupyan, G. (2008). Developing object concepts in infancy: An associative learning perspective: I. Introduction. *Monographs of the Society for Research in Child Development*.
- Rapp, R., & Wettler, M. (1991). Prediction of free word associations based on Hebbian learning. Paper presented at the international joint conference on neural networks, Singapore.
- Rehder, B. (2006). When similarity and causality compete in category-based property generalization. *Memory & Cognition*, 34, 3–16.
- Rehder, B. (2009). Causal-based property generalization. *Cognitive Science*, 33, 301–344.
- Rehder, B., & Hastie, R. (2001). Causal knowledge and categories: The effects of causal beliefs on categorization, induction, and similarity. *Journal of Experimental Psychology: General*, 130, 323–360.
- Rossion, B., & Pourtois, G. (2004). Revisiting Snodgrass and Vanderwart's object pictorial set: The role of surface detail in basic-level object recognition. *Perception*, 33, 217–236.
- Shafto, P., & Coley, J. D. (2003). Development of categorization and reasoning in the natural world: Novices to experts, naive similarity to ecological knowledge. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 29, 641–649.
- Shafto, P., Coley, J. D., & Baldwin, D. (2007a). Effects of time pressure on context-sensitive property induction. *Psychonomic Bulletin & Review*, 14, 890–894.
- Shafto, P., Coley, J. D., & Vitkin, A. Z. (2007b). Availability in category-based induction. In A. Feeney & E. Heit (Eds.), *Inductive reasoning*. Cambridge, UK: Cambridge University Press.
- Shafto, P., Kemp, C., Bonawitz, E. B., Coley, J. D., & Tenenbaum, J. B. (2008). Inductive reasoning about causally transmitted properties. *Cognition*, 109, 175–192.
- Siegal, M., & Share, L. (1990). Contamination sensitivity in young children. *Developmental Psychology*, 26, 455–458.
- Sloman, S. A. (1993). Feature-based induction. *Cognitive Psychology*, 25, 231–280.
- Sloman, S. A. (2005). *Causal models: How people think about the world and its alternatives*. New York: Oxford University Press.
- Sloutsky, V. M. (2010). From perceptual categories to concepts: What develops? *Cognitive Science*, 34, 1244–1286.
- Sloutsky, V. M., & Fisher, A. V. (2004). When development and learning decrease memory: Evidence against category-based induction in children. *Psychological Science*, 15, 553–558.
- Sloutsky, V. M., & Fisher, A. V. (2008). Attentional learning and flexible induction: How mundane mechanisms give rise to smart behaviors. *Child Development*, 79, 639–651.
- Smiley, S. S., & Brown, A. L. (1979). Conceptual preference for thematic or taxonomic relations: A nonmonotonic trend from preschool to old age. *Journal of Experimental Child Psychology*, 28, 437–458.
- Smith, L. A., & Williams, J. M. (2007). "It's the X and Y thing": Cross-sectional and longitudinal changes in children's understanding of genes. *Research in Science Education*, 37, 407–422.
- Sobel, D. M., & Kirkham, N. Z. (2007). Bayes nets and babies: Infants' developing statistical reasoning abilities and their representation of causal knowledge. *Developmental Science*, 10, 298–306.
- Spence, D. P., & Owens, K. C. (1990). Lexical co-occurrence and association strength. *Journal of Psycholinguistic Research*, 19, 317–330.

- Springer, K., & Belk, A. (1994). The role of physical contact and association in early contamination sensitivity. *Developmental Psychology*, 30, 864–868.
- Tenenbaum, J. B., Kemp, C., & Shafto, P. (2007). Theory-based Bayesian models of inductive reasoning. In A. Feeney & E. Heit (Eds.), *Inductive reasoning*. Cambridge, UK: Cambridge University Press.
- Venville, G., & Donovan, J. (2007). Developing Year 2 students' theory of biology with concepts of the gene and DNA. *International Journal of Science Education*, 29, 1111–1131.
- Vitkin, A. Z., Coley, J. D., & Hu, R. (2005). Children's use of relevance in open-ended induction in the domain of biology. In B. G. Bara, L. Barsalou, & M. Bucciarelli (Eds.), *Proceedings of the 27th annual conference of the Cognitive Science Society* (pp. 2319–2324). Mahwah, NJ: Lawrence Erlbaum.
- Waldmann, M. R. (2000). Competition among causes but not effects in predictive and diagnostic learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 26, 53–76.
- Wellman, H. M., Hickling, A. K., & Schult, C. A. (1997). Young children's psychological, physical, and biological explanations. *New Directions in Child Development*, 75, 7–25.